A new model for hadron collisions

Butch Cassidy and the Sundance Kid. Copyright: Twentieth Century Fox Films Inc.

Based on:

- T. Sjöstrand + PS, “Transverse-Momentum-Ordered Showers and Interleaved Multiple Interactions”, hep-ph/0408302 (in print, EPJC).
- T. Sjöstrand + PS, “Multiple Interactions and the Structure of Beam Remnants”, JHEP 0403 (2004) 053.

THIS TALK IN A NUTSHELL

It's about two things in hadron–hadron collisions:

1. The average hadron–hadron collision (mostly inelastic QCD forward scattering).
2. The extra stuff that goes on 'underneath' a hard scattering, e.g. when a Higgs or Z^0 is produced.

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In the past, descriptions have been limited to crude models and/or parametrizations.

We are now developing a new model for hadron collisions, based on physical principles, and unifying the description of 1 & 2 (and everything inbetween).

WHY BOTHER?

- QCD point of view: hadron collisions are highly complex, while present descriptions are not.
  Should be possible to gain further physics insight.

- Any reliable extrapolation to LHC energies will require such insight.
  Simple parametrizations are not sufficient.

- Random and systematic fluctuations in the underlying activity can impact precision measurements and New Physics searches:
  More reliable understanding is needed.

- Lots of fresh data from Tevatron (courtesy R. Field):
  Great topic for phenomenology right now

WHAT'S HOT?

Some topics we are currently thinking about are:

1. Jet Universality.
2. Absence of Colour Reconnections.

These are two standard assumptions made in shower/ fragmentation Monte Carlos, which essentially translate to:

1. Hadronization is the same at pp, ep, and $\mathrm{e^+e^-}$ colliders.
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With a more physical model, we are able to give more serious interpretations of the CDF data. We see indications of a large amount of colour reconnections, possibly connected with a breakdown of jet universality.

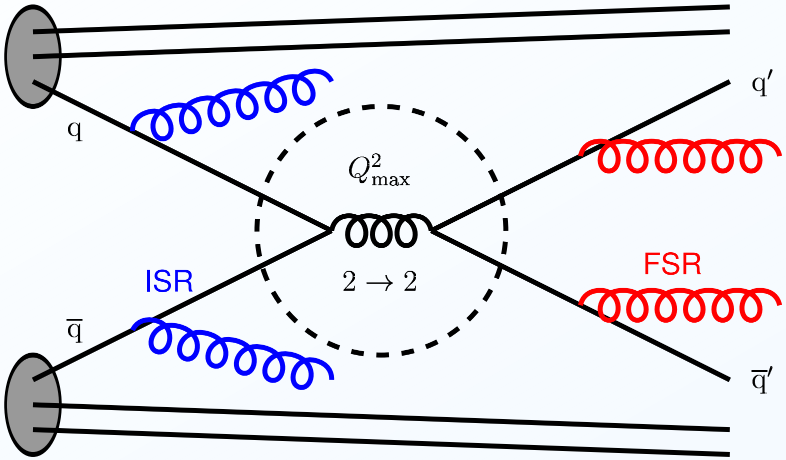
Overview

- Introduction:
  - A general view of hadron collisions.
  - Existing approaches.
- The new framework.
  - $p_\perp$–ordered showers: FSR and ISR.
  - Interleaved multiple interactions.
  - Model tests.
- Outlook.

A general view of hadron collisions

1 hadron collision =

$$(2 \to 2 \oplus \underbrace{\text{ISR} \oplus \text{FSR}}_{\text{Eff. resum. of multiple (semi-)soft gluon emission effects}} \oplus \text{UE}) \otimes \text{hadronisation etc.}$$



+ additional interactions!

+ hadronisation!

+ hadron decays!

+ more?

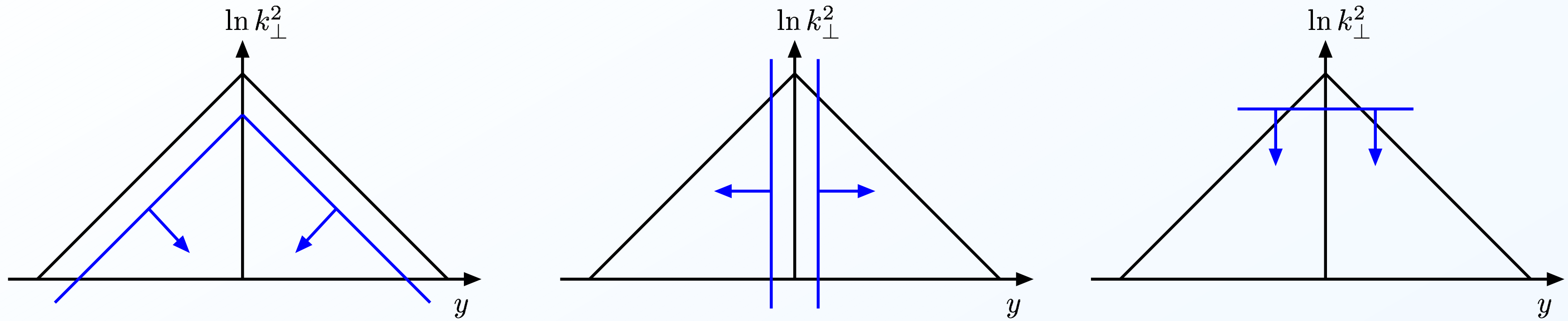
- $2 \to 2$: ‘hard subprocess’ (on–shell).
- ISR: Initial–State Radiation (spacelike).
- FSR: Final–State Radiation (timelike).
- UE: Underlying Event – any additional (perturbative) activity.

PARTON SHOWERS

Showers: Existing Approaches

Essential difference: ordering variables.

consider e.g. gluon emission off a $q_1\overline{q}_2$ system.



PYTHIA/JETSET	HERWIG	ARIADNE
m^2 ($-m^2$ for ISR)	$\sim E^2\theta^2$	$p_\perp^2$
High–virtuality ems. first. (may be at 'small' angles.)	Large–angle ems. first. (may be soft.)	Large–$p_\perp$ ems. first.

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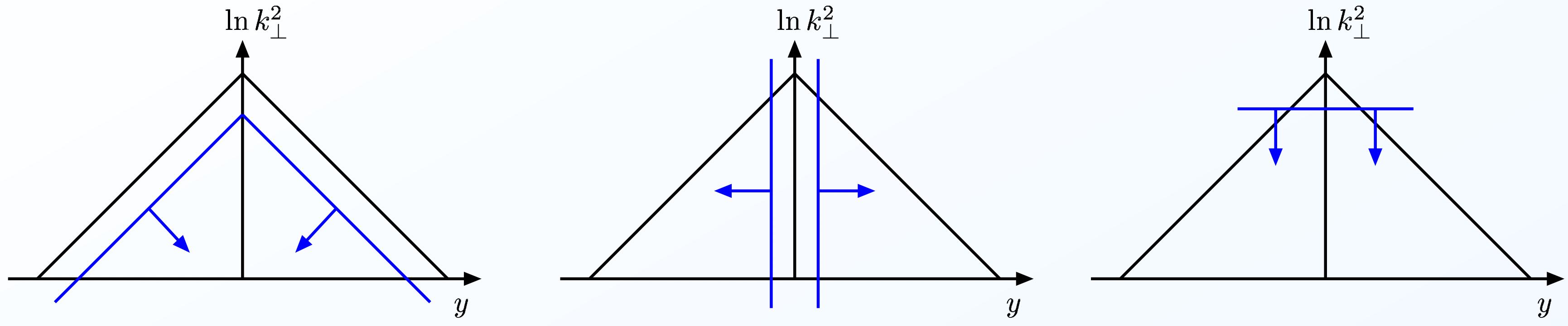

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Another important difference is the way recoils are assigned, i.e. how the on–shell kinematics prior to the branching is reinterpreted to include the virtual (branching) leg.

Existing Showers: Pros and Cons

- HERWIG: $Q^2 \approx E^2(1-\cos\theta) \approx E^2\theta^2/2$

  $+$ angular ordering $\Rightarrow$ coherence inherent

  $-$ emissions not ordered in hardness

  $-$ emissions do not cover full phase space (messy kinematics)

  $-$ kinematics constructed at the very end

- PYTHIA: $Q^2 = m^2$ (timelike) or $= -m^2$ (spacelike)

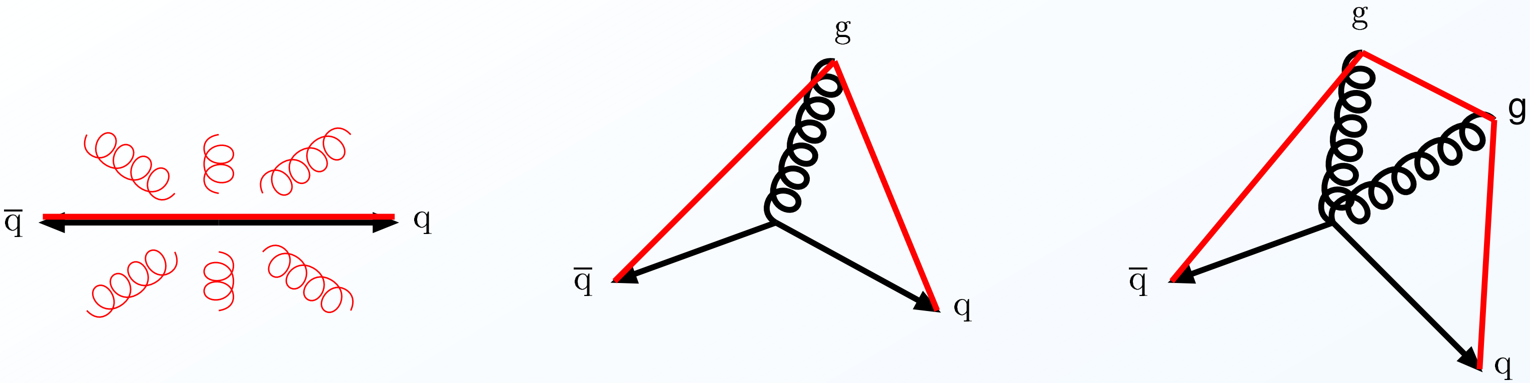
  $+$ convenient merging with ME

  $\pm$ emissions ordered in (some measure of) hardness

  $-$ coherence by brute force $\Rightarrow$ approximate

  $-$ kinematics constructed when daughter masses known

Existing Showers: Pros and Cons



- ARIADNE: $Q^2 = p_\perp^2$, (final-state) dipole emission
  - $+\ p_\perp$ ordering $\Rightarrow$ coherence inherent
  - $+$ Lorentz invariant
  - $+$ emissions ordered in hardness
  - $+$ kinematics constructed after each branching (partons explicitly on-shell until they branch)
  - $+$ showers can be stopped and restarted at any $p_\perp$ scale. $\Rightarrow$ good for ME/PS matching (L-CKKW, real+fictitious showers)

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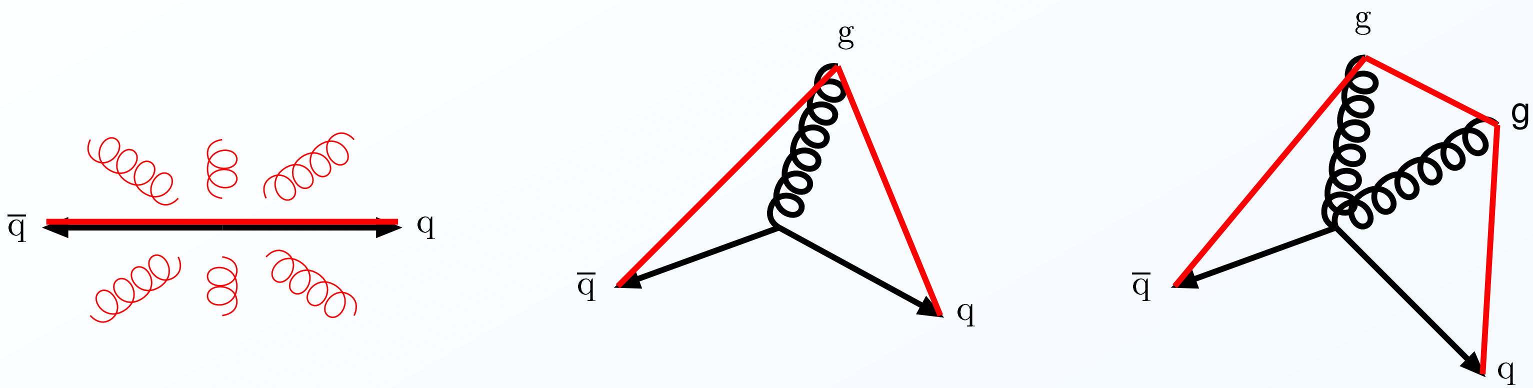

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    $\Rightarrow$ good for ME/PS matching (L-CKKW, real+fictitious showers)
  - $-$ $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ artificial
  - $-$ not so suited for pp on its own: ISR is primitive in ARIADNE.

Why Develop a New Shower?

Incorporate several of the good points of the dipole formalism within the shower approach

$\pm$ explore alternative $p_\perp$ definitions

$+$ $p_\perp$ ordering $\Rightarrow$ coherence inherent

$+$ Merging with Matrix Elements unproblematic
(unique $p_\perp^2 \leftrightarrow Q^2$ mapping; same z)

$+$ $\mathrm{g} \to \mathrm{q}\overline{\mathrm{q}}$ natural

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    (not yet worked-out for ISR+FSR)
  - $+$ allows to combine $p_\perp$ evolutions of showers and multiple interactions $\to$ *common* (competing) evolution of ISR, FSR, and MI!

$\equiv$ 'Interleaved Multiple Interactions'

UNDERLYING EVENT, MINIMUM BIAS

Multiple Interactions

Why *multiple perturbative interactions*?

Consider perturbative QCD $2 \to 2$ scattering:

dominated by t-channel gluon exchange $\Rightarrow$ IR divergent:

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_\perp^2} \propto \frac{1}{t^2} \sim \frac{1}{p_\perp^4}$$

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$\Longrightarrow$ '2-jet' cross sect

$$\sigma_{2\to 2}(p_{\perp\mathrm{min}}) = \int_{p_{\perp\mathrm{min}}}^{\sqrt{s}/2} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp}\,\mathrm{d}p_\perp \propto \frac{1}{p_{\perp\mathrm{min}}^2}$$

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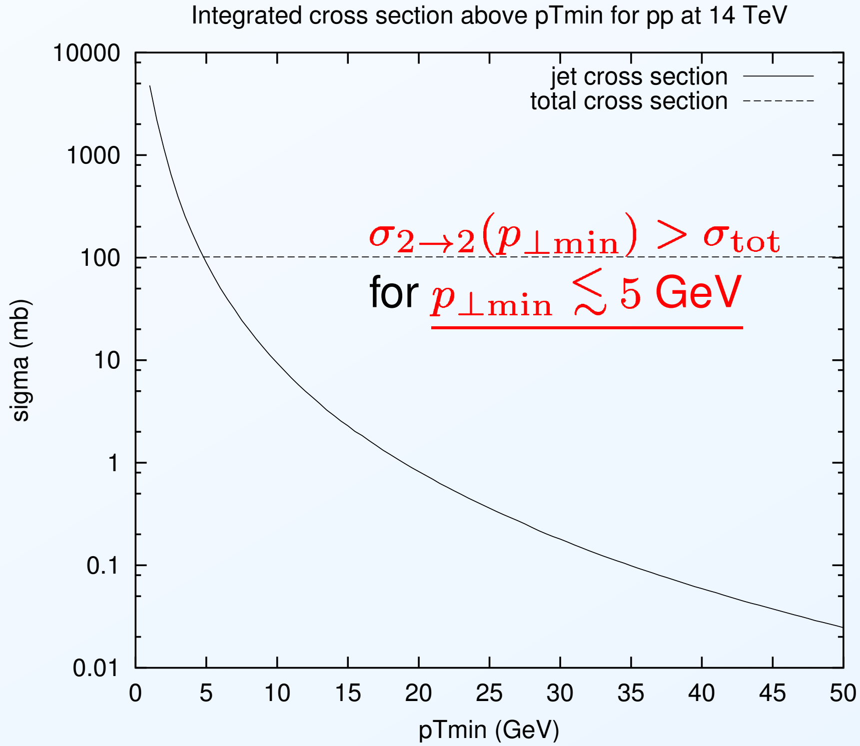
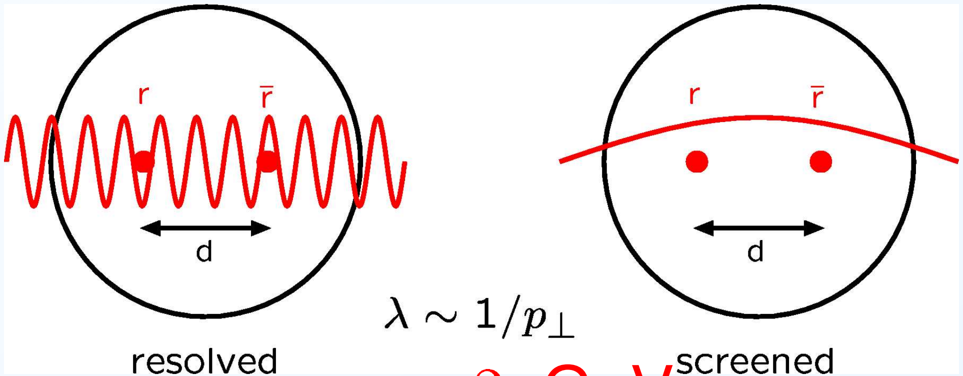


What’s going on?

1. **Multiple interactions (MI)!**
   - Must exist (hadrons are composite!)
   - σ_{tot}: hadron-hadron collisions. $\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n$
   - $\sigma_{2\to2}$: parton–parton collisions. $\sigma_{2\to2} = \sum_{n=0}^{\infty} n\,\sigma_n$
   - $\sigma_{2\to2} > \sigma_{\mathrm{tot}} \Longleftrightarrow \langle n \rangle > 1$

2. **Breakdown of pQCD, colour screening.**



$p_{\perp 0} \sim 2$ GeV

Multiple Interactions — Direct Evidence

Basic idea : expect four pair-wise balancing jets in double parton scattering (DPS) but not in double bremsstrahlung emission.

- **AFS** : 4-jet events at $E_\perp > 4$ GeV in 1.8 units of η. Project out 2 pairs of jets and study imbalancing variable, $I = p^2_{\perp 1} + p^2_{\perp 2}$. Excess of events with small I.
- **CDF**: Extraction by comparing double parton scattering (DPS) to a mix of two separate scatterings. Sample: 14000 $\gamma/\pi^0 + 3j$ events. Strong signal observed, 53% DPS
- (Note irony: only plot made was comparison to PYTHIA with MI switched *off*!)

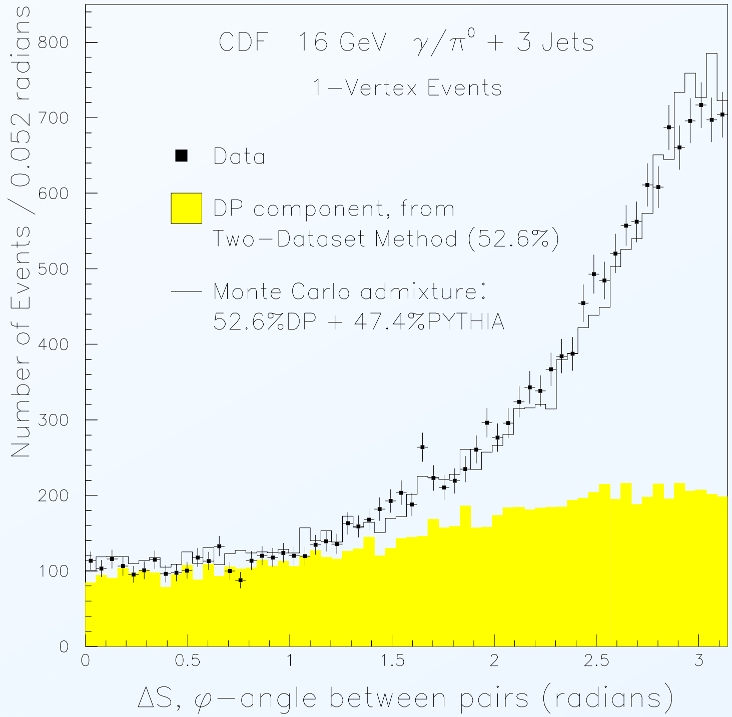


Figure 1: ΔS distribution for 1VTX data (points). The DP component to the data, determi...
two-dataset method to be 52.6% of the sample, is shown as the shaded region (the shape is...

Multiple Interactions — Indirect Verifications

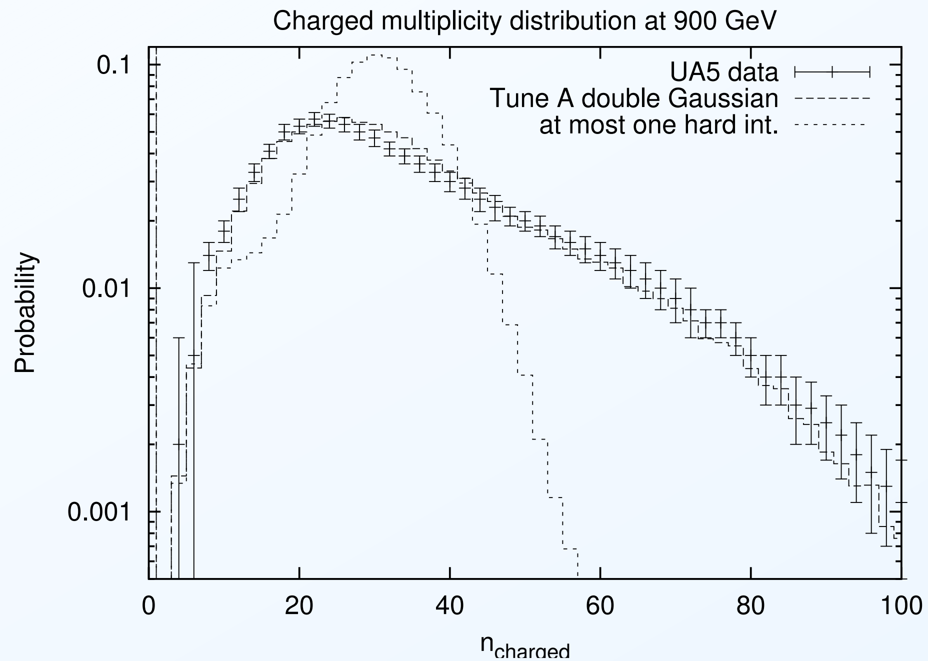
Basic idea :

- **Hadronization alone produces roughly Poissonian fluctuations in multiplicity.**
- **Additional soft interactions can 'mess up' colour flow** $\rightarrow$ larger fluctuations.

UA5: (900 GeV)

$\langle n_{\rm ch}\rangle =$35.6,

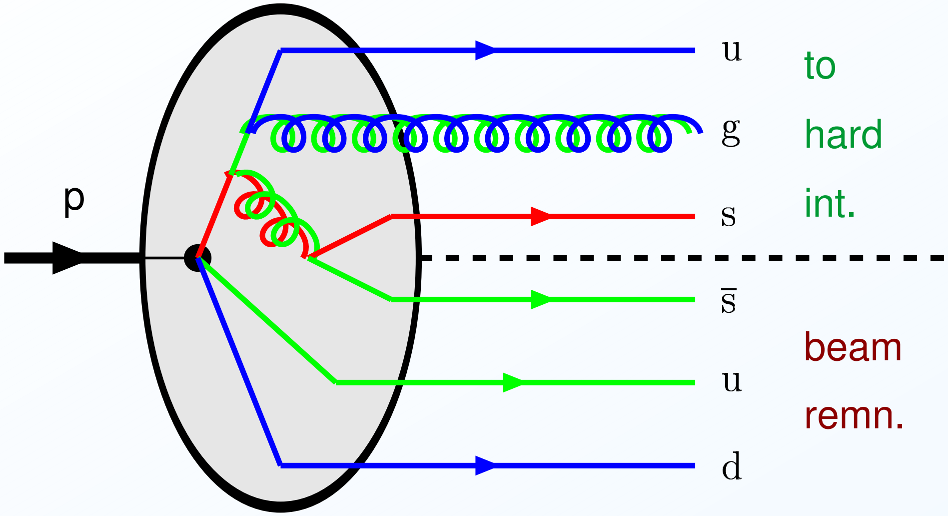
$\sigma_{n_{\rm ch}} =$19.6.



- **+ forward–backward correlations (UA5 , E735)**
- **+ pedestal effect (UA1 , CDF , H1), ...**

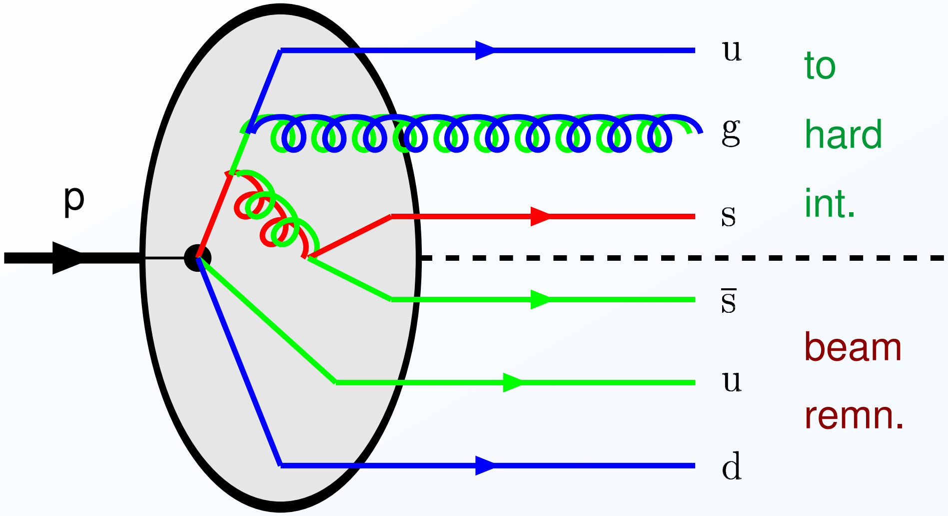
BEAM REMNANTS, FRAGMENTATION

Completing the picture



How are the hard scattering initiators and beam remnant partons correlated:

Completing the picture



How are the hard scattering initiators and beam remnant partons correlated:

- ☞ In impact parameter?
- ☞ In flavour?
- ☞ In longitudinal momentum?
- ☞ In colour?
- ☞ In (primordial) transverse momentum?

(How) are the showers correlated / intertwined?

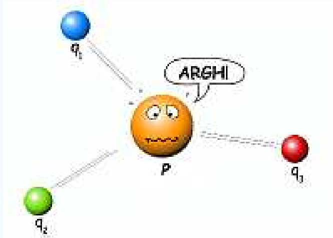
(...) $\otimes$ Hadronization.

- Imagine placing a stick o' dynamite inside a proton, imparting the 3 valence quarks with large momenta relative to each other.

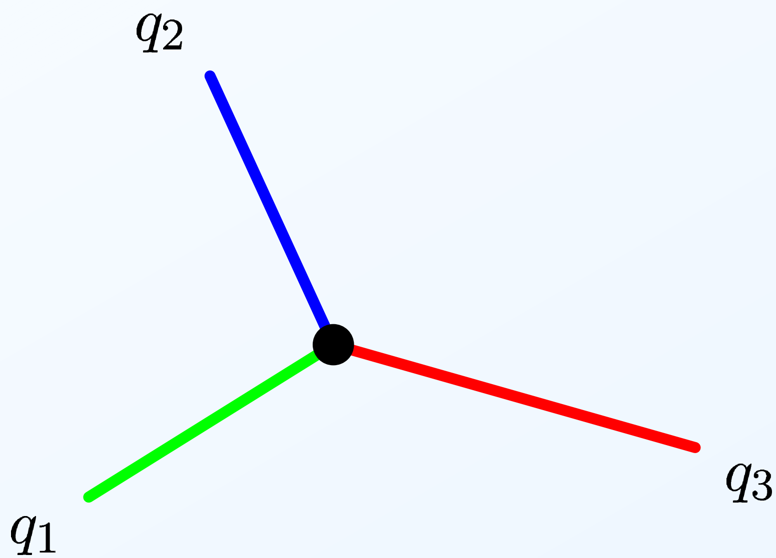
'Ordinary' colour topology

(e.g. $Z^0 \to q\bar{q}$):

'Baryonic' colour topology

(e.g. 

):



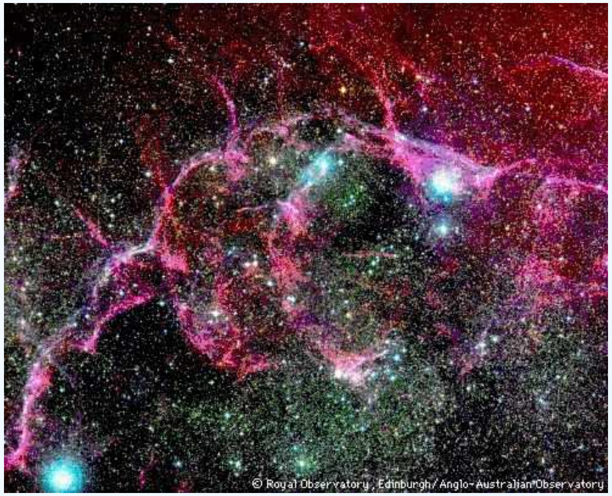
- Fragmentation of 'baryonic' topology recently developed.

[T. Sjöstrand + PS, "Baryon Number Violation and String Topologies", Nucl.Phys. B659 (2003) 243.]

THE NEW MODEL

Interactions

+ showers



+ remnants

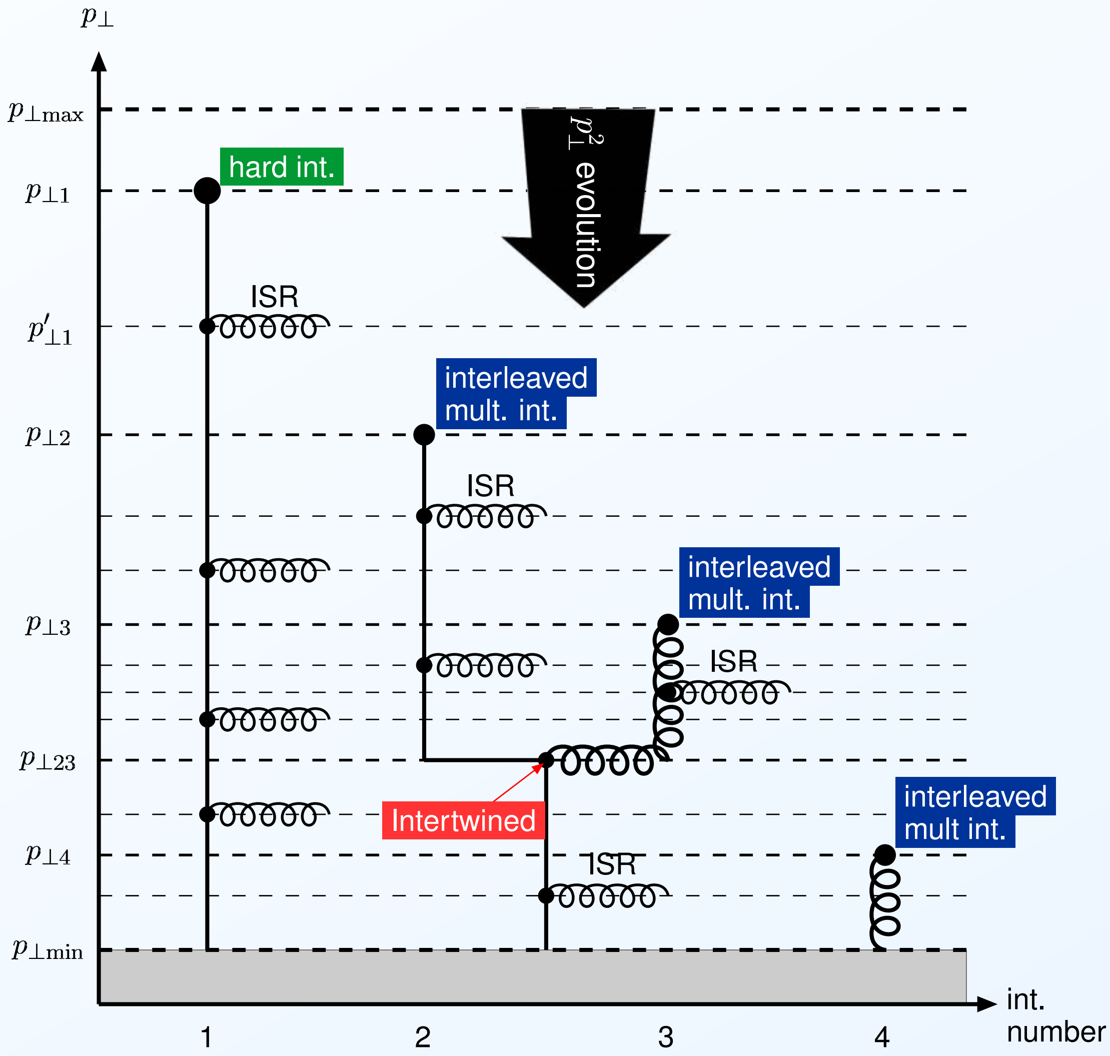
The New Framework

- All the reasons mentioned at the beginning of the talk led us to develop a new sophisticated model for UE (and min–bias) $\rightarrow$ ‘intermediate model’.
- But still each interaction was considered separately, with *its* set of ISR and FSR.
- That’s probably not the way it happens in real life...

The New Framework

The new picture: start at the most inclusive level, $\boxed{2 \to 2}$. Add exclusivity progressively by evolving *everything* downwards in *one* common sequence:

$\to$ **Interleaved evolution**



($\to$ also possible to have interactions *intertwined* by the ISR activity?)

The New Framework

The building blocks:

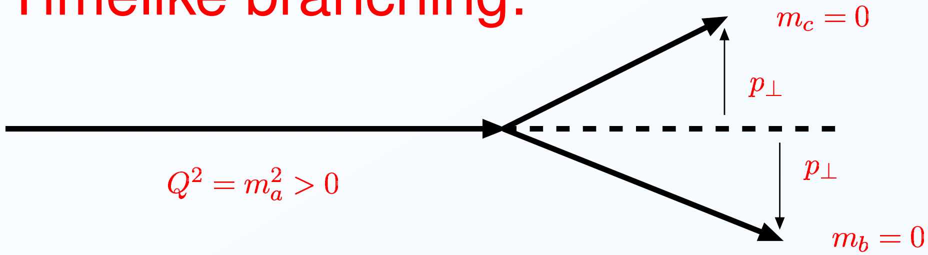
- $p_\perp$–ordered multiple interactions. ✔
- $p_\perp$–ordered initial–state parton showers. ✔
- $p_\perp$–ordered final–state parton showers. ✔
- $p_\perp$ used as scale in α_s and in PDF's. ✔
- (Model for) correlated multi–parton densities. ✔
- Beam remnant hadronization model. ✔
- Model for initial state colour correlations. (✔ — but far from perfect!)
- Other phenomena? (e.g. colour reconnections (✔), ...)
- Realistic tunes to data (so far only for FSR...)

$p_\perp$–ordered showers: Simple Kinematics

Consider branching $a \to bc$ in lightcone coordinates $p^\pm = E \pm p_z$

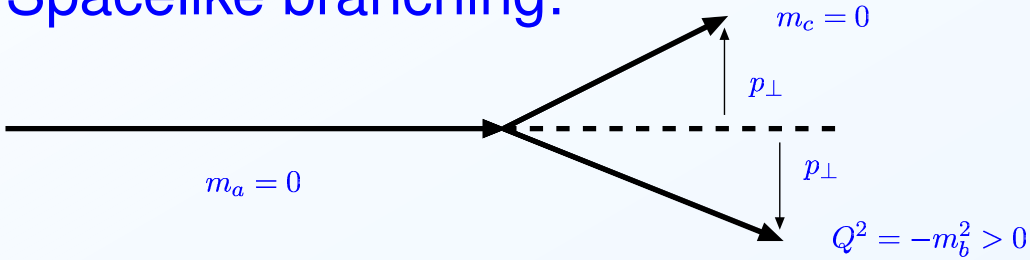
$$\left.\begin{aligned} p_b^+ &= z p_a^+ \\ p_c^+ &= (1-z) p_a^+ \\ p^- &\ \text{conservation} \end{aligned}\right\} \Longrightarrow m_a^2 = \frac{m_b^2 + p_\perp^2}{z} + \frac{m_c^2 + p_\perp^2}{1-z}$$

Timelike branching:



$$p_\perp^2 = z(1-z)Q^2$$

Spacelike branching:



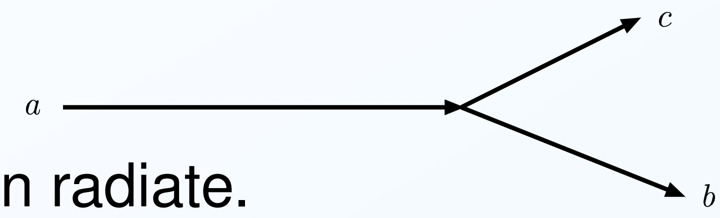
$$p_\perp^2 = (1-z)Q^2$$

Guideline, not final $p_\perp$!

$\mathrm{p}_\perp$–ordered showers: General Strategy (1)

1) *Define* $\mathrm{p}^2_{\perp\mathrm{evol}} = z(1-z)Q^2$ for FSR

$\mathrm{p}^2_{\perp\mathrm{evol}} = (1-z)Q^2$ for ISR



2) Find list of *radiators* = partons that can radiate.
Evolve them all *downwards* in $\mathrm{p}_{\perp\mathrm{evol}}$ from common $p_{\perp\mathrm{max}}$

$$\mathrm{d}\mathcal{P}_a = \frac{\mathrm{d}\mathrm{p}^2_{\perp\mathrm{evol}}}{\mathrm{p}^2_{\perp\mathrm{evol}}} \frac{\alpha_\mathrm{s}(\mathrm{p}^2_{\perp\mathrm{evol}})}{2\pi} P_{a\to bc}(z)\,\mathrm{d}z\;\exp\left(-\int_{\mathrm{p}^2_{\perp\mathrm{evol}}}^{p^2_{\perp\mathrm{max}}} \cdots\right)$$

$$\mathrm{d}\mathcal{P}_b = \frac{\mathrm{d}\mathrm{p}^2_{\perp\mathrm{evol}}}{\mathrm{p}^2_{\perp\mathrm{evol}}} \frac{\alpha_\mathrm{s}(\mathrm{p}^2_{\perp\mathrm{evol}})}{2\pi} \frac{x' f_a(x', \mathrm{p}^2_{\perp\mathrm{evol}})}{x f_b(x, \mathrm{p}^2_{\perp\mathrm{evol}})} P_{a\to bc}(z)\,\mathrm{d}z\;\exp\left(-\cdots\right)$$

Pick the one with *largest* $\mathrm{p}_{\perp\mathrm{evol}}$ to undergo branching; also gives z.

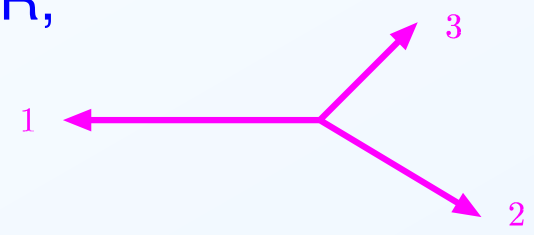
3) *Derive* $Q^2 = \mathrm{p}^2_{\perp\mathrm{evol}}/z(1-z)$ for FSR

$Q^2 = \mathrm{p}^2_{\perp\mathrm{evol}}/(1-z)$ for ISR

$p_\perp$–ordered showers: General Strategy (2)

4) Find *recoiler* = parton to take recoil when radiator is pushed off-shell
   usually nearest colour neighbour for FSR
   incoming parton on other side of event for ISR

5) Interpret z as *energy fraction* (not lightcone)
   in radiator+recoiler rest frame for FSR,
   in mother-of-radiator+recoiler rest frame for ISR,
   so that *Lorentz invariant*
   $(2E_i/E_{\mathrm{cm}} = 1 - m_{jk}^2/E_{\mathrm{cm}}^2)$
   and straightforward match to matrix elements



6) Do *kinematics* based on Q^2 and z,
   a) assuming yet unbranched partons on-shell
   b) shuffling energy–momentum from recoiler as required

7) Continue evolution of all radiators from recently picked $\mathrm{p}_{\perp\mathrm{evol}}$.
   Iterate until no branching above $p_{\perp\mathrm{min}}$.
   $\Rightarrow$ One combined sequence $p_{\perp\mathrm{max}} > p_{\perp 1} > p_{\perp 2} > \ldots > p_{\perp\mathrm{min}}$.

$p_\perp$–ordered showers: Some Details

FSR Evolution:

- Massive quarks: $\mathrm{p}^2_{\perp\mathrm{evol}} = z(1-z)(m^2 - m_Q^2)$
  $\Rightarrow m^2 \to m_Q^2$ when $\mathrm{p}^2_{\perp\mathrm{evol}} \to 0$.
- Special treatment of narrow resonances (e.g. top).

ISR Evolution:

- Massive quarks: $\mathrm{p}^2_{\perp\mathrm{evol}} = (1-z)(Q^2 + m_Q^2) = m_Q^2 + \mathrm{p}^2_{\perp\mathrm{LC}}$
  $\Rightarrow$ Light–Cone $\mathrm{p}^2_{\perp\mathrm{LC}} \to 0$ when $\mathrm{p}^2_{\perp\mathrm{evol}} \to m_Q^2$.
- Backwards evolution uses correlated pdf's at scales where more than 1 interaction is resolved.

Both ISR and FSR:

- ME merging by veto for many SM+MSSM processes.
- Gluon polarization $\to$ asymmetric φ distribution.

Correlated PDF's in flavour and $\mathbf{x}_i$

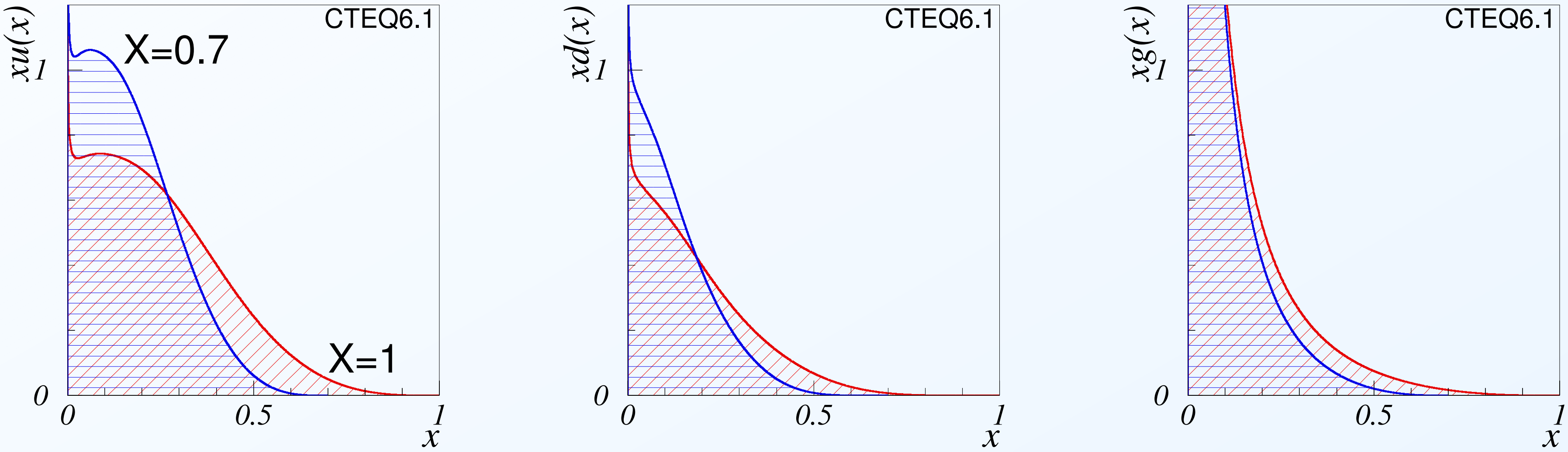
Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out of it?

1. Overall momentum conservation (old):

Starting point: simple scaling ansatz in x.

For the n'th scattering:

$$x \in [0, X] \;\; ; \;\; X = 1 - \sum_{i}^{n-1} x_i \implies f_n(x) \sim \frac{1}{X} f_0\left(\frac{x}{X}\right)$$



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Normalization and shape:

✧ If valence quark knocked out.

$\rightarrow$ Impose valence counting rule: $\displaystyle\int_0^X q_{fn}^{\mathrm{val}}(x, Q^2)\,\mathrm{d}x = N_{fn}^{\mathrm{val}}$.

✧ If sea quark knocked out.

$\rightarrow$ Postulate "companion antiquark": $\displaystyle\int_0^{1-x_s} q_f^{\mathrm{cmp}}(x; x_s)\,\mathrm{d}x = 1.$

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- But then momentum sum rule is violated:

$$\int_0^X x\Big(\sum_f q_{fn}(x, Q^2) + g_n(x, Q^2)\Big)\mathrm{d}x \neq X$$

  $\rightarrow$ Assume sea+gluon fluctuates up when a valence quark is removed and down when a companion quark is added.

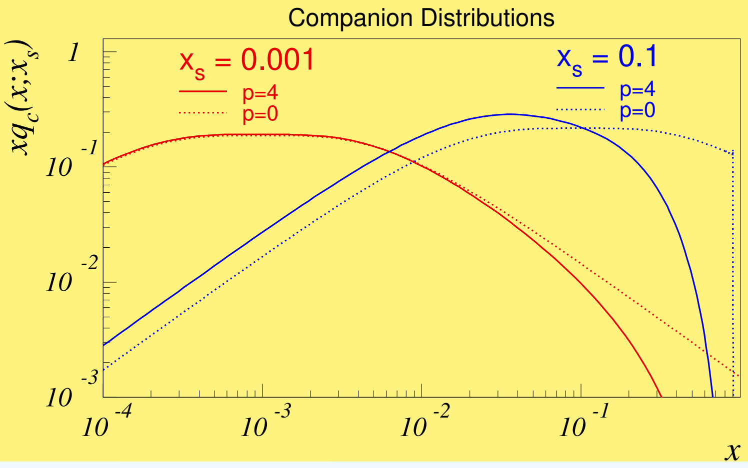
Remnant PDFs

$$\text{quarks}: \quad q_{fn}(x) = \frac{1}{X}\left[\frac{N_{fn}^{\text{val}}}{N_{f0}^{\text{val}}} q_{f0}^{\text{val}}\left(\frac{x}{X}, Q^2\right) + a\, q_{f0}^{\text{sea}}\left(\frac{x}{X}, Q^2\right) + \sum_j q_{f0}^{\text{cmp}_j}\left(\frac{x}{X}; x_{s_j}\right)\right]$$

$$q_{f0}^{\text{cmp}}(x; x_s) = C\,\frac{\tilde{g}(x+x_s)}{x+x_s} P_{g\to q_f \bar{q}_f}\left(\frac{x_s}{x+x_s}\right) \quad ; \quad \left(\int_0^{1-x_s} q_{f0}^{\text{cmp}}(x; x_s)\,\mathrm{d}x = 1\right)$$

$$\text{gluons}: \quad g_n(x) = \frac{a}{X} g_0\left(\frac{x}{X}, Q^2\right)$$

$$a = \frac{1 - \sum_f N_{fn}^{\text{val}} \langle x_{f0}^{\text{val}} \rangle - \sum_{f,j} \langle x_{f0}^{\text{cmp}_j} \rangle}{1 - \sum_f N_{f0}^{\text{val}} \langle x_{f0}^{\text{val}} \rangle}$$



Used to select $p_\perp$-ordered $2 \to 2$ scatterings, and to perform backwards DGLAP shower evolution.

Intermezzo 1: exit perturbation theory

Perturbation theory got us:

- A set of interactions, with showers, starting from $k_\perp = 0$ initiator partons.
- A set of partons left behind in the beam remnants, with only flavours known at this point (by flavour conservation).
- A total $1 - X$ of longitudinal momentum has been removed from each beam remnant.

Hurdles remaining:

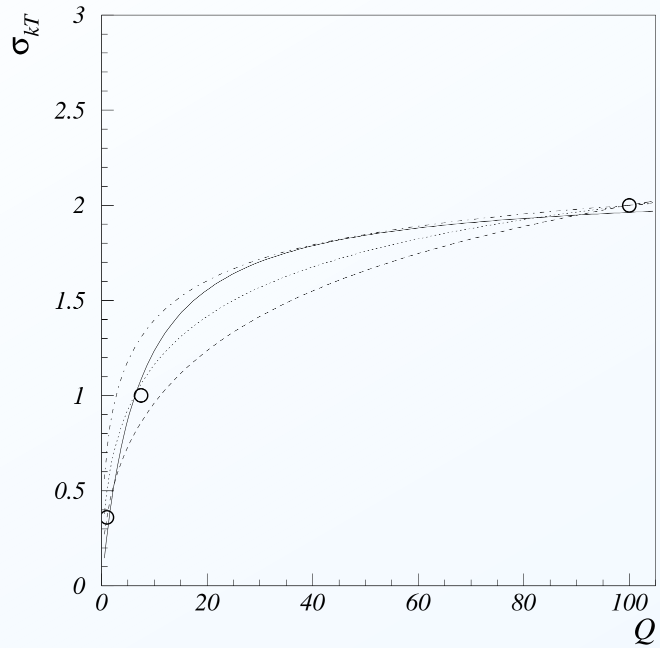
- Confinement effects $\to$ primordial $k_\perp$. How much? Recoils?
- What is the momentum sharing in the remnants?
- How are initiator and remnant partons correlated in colour?
- How do the remnant systems hadronize?

Confinement and primordial $\mathbf{k}_\perp$

- Confined wavefunctions $\to k_\perp = \hbar / r_\mathrm{p} \sim \Lambda_\mathrm{QCD}$.
- Empirically, one notes a need for larger values.

$$\frac{\mathrm{d}^2 N}{\mathrm{d}k_x \mathrm{d}k_y} \propto e^{-k_\perp^2/\sigma^2(Q)}$$

$\sigma(1\ \mathrm{GeV}) \approx 0.36\ \mathrm{GeV}\ (\mathit{hadr.})$
$\sigma(10\ \mathrm{GeV}) \approx 1\ \mathrm{GeV}\ (\mathit{EMC})$
$\sigma(m_Z) \approx 2\ \mathrm{GeV}\ (\mathit{Tevatron})$



Solid: $\dfrac{2.1Q}{7+Q}$ (hardcoded default)

Dashed: $\dfrac{4\sqrt{Q}}{10+\sqrt{Q}}$

Dotted: $\dfrac{3\sqrt{Q}}{5+\sqrt{Q}}$

Dot-dashed: $\dfrac{2.5\sqrt{Q}}{2.5+\sqrt{Q}}$

- **Recoils**: along colour neighbours (or chain of neighbours) or onto all initiators and beam remnant partons equally. (k_z rescaled to maintain energy conservation.)

Sharing of $\mathbf{x}_{\mathrm{rem}}$ in beam remnant

Each hard scattering subsystem has light-cone momenta:

$$
\begin{aligned}
p_+ &= \gamma(E_1^{CM(z)} + E_2^{CM(z)}) + \gamma\beta(E_1^{CMz} + E_2^{CMz}) \\
&= \sqrt{\tfrac{1+\beta}{1-\beta}\left(\hat{s} + (\vec{p}_\perp^{(1)} + \vec{p}_\perp^{(2)})^2\right)} \\
&= \sqrt{\tfrac{x_1}{x_2}}\sqrt{\hat{s}_\perp} \\
p_- &= \gamma(1-\beta)(E_1^{CM(z)} + E_2^{CM(z)}) = \sqrt{\tfrac{x_2}{x_1}}\sqrt{hats_\perp}
\end{aligned}
$$

Remaining light-cone momenta available for BR:

$$
p_{rem}^+ = \sqrt{s} - \sum_i \sqrt{\tfrac{x_i^{(+)}}{x_i^{(-)}}\left(hats_i + (\vec{p}_{\perp i}^{(+)} + \vec{p}_{\perp i}^{(-)})^2\right)} \quad ; \quad p_{rem}^- = \sqrt{s} - \sum_i \sqrt{\tfrac{x_i^{(-)}}{x_i^{(+)}}\left(hats_i + (\vec{p}_{\perp i}^{(+)} + \vec{p}_{\perp i}^{(-)})^2\right)}
$$

Def:"$\pm$" side BR partons have fractions $x_{j/k}$ of $p_{rem}^{\pm}$.

- ✧ Assume $x_{j,k}$ di stributed according to 'remnant' pdf's and fragmentation functions (with (E, p) conserved).
- ✧ NB: composite BR systems (w. pion/gluon clouds?) $\rightarrow$ larger x?

Intermezzo 2: now it gets tougher

We have arrived at:

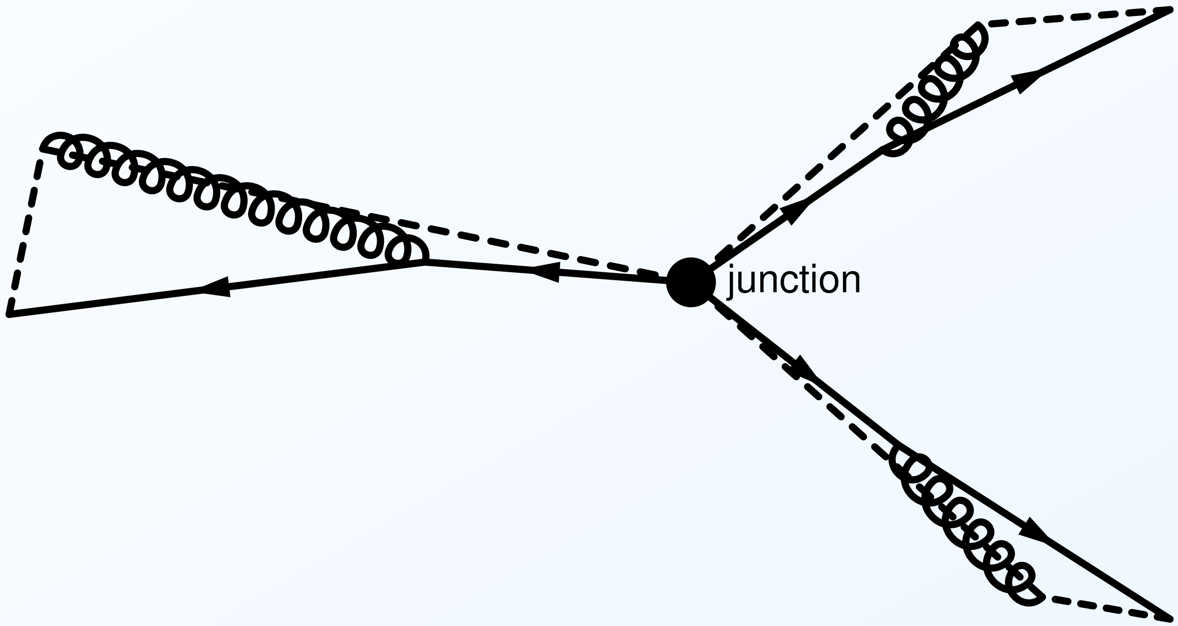
- A set of $p_\perp$-ordered interactions, with showers, taking into account non-zero primordial $k_\perp$ effects.
- A set of partons (possibly diquarks etc) left behind in the beam remnants, whose flavours are known and whose kinematics have been worked out (i.e. x and $\vec{k}_\perp$).

But life grants nothing to us mortals without hard work

- How are initiator and remnant partons correlated in colour?
- How do remnant systems hadronize?

Hadronization: String Junctions

- Fundamental properties of QCD vacuum suggest string picture still applicable.
- Baryon wavefunction building and string energy minimization $\Longrightarrow$ picture of 3 string pieces meeting at a 'string junction'.



(Warning: This picture was drawn in a "pedagogical projection" where distances close to the center are greatly exaggerated!)

Junction Fragmentation

How does the junction move?

- A junction is a topological feature of the string confinement field: $V(r) = \kappa r$. Each string piece acts on the other two with a constant force, $\kappa \vec{e}_r$.
- $\Longrightarrow$ in junction rest frame (JRF) the angle is 120° between the string pieces.
- Or better, 'pull vectors' lie at 120°:

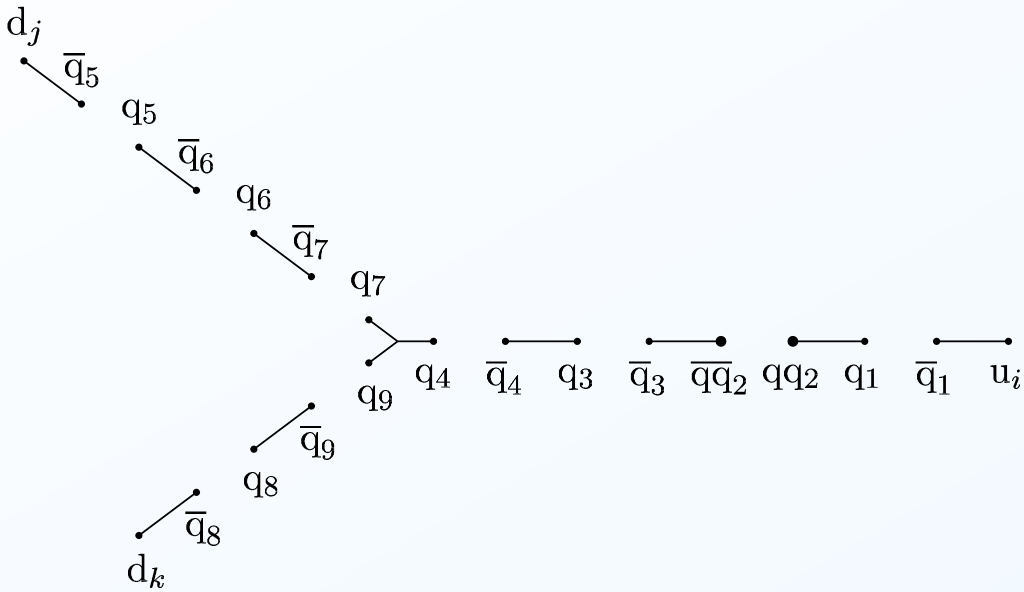
$$p^{\mu}_{\mathrm{pull}} = \sum_{i=1,N} p^{\mu}_i e^{-\sum_{j=1}^{i-1} \frac{E_j}{\kappa}}$$

(since soft gluons 'eaten' by string)

- Note: the junction motion also determines the baryon number flow!)

Junction Fragmentation

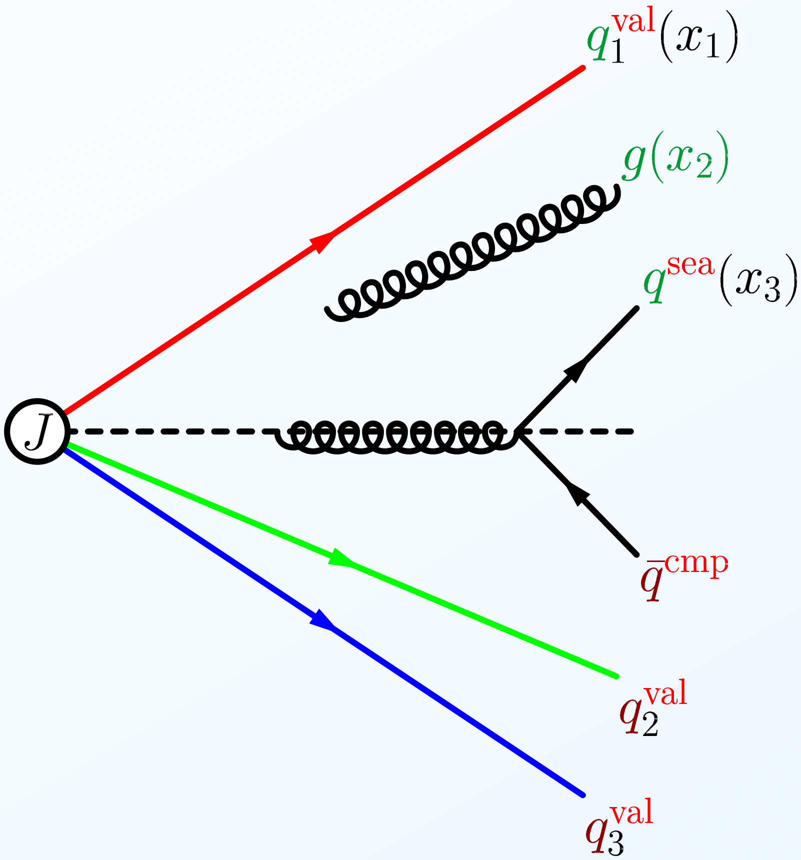
How does the system fragment?



- First 2 pieces fragmented outwards–in, junction baryon formed around junction, last string piece fragmented as ordinary $q\overline{q}$ string.
- NB: Other topologies also possible (junction–junction strings, junction–junction annihilation).

Colour Correlations and String Topologies

- But how to draw the strings? How are initiator and beam remnant partons colour connected to each other?



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Colour Correlations and String Topologies

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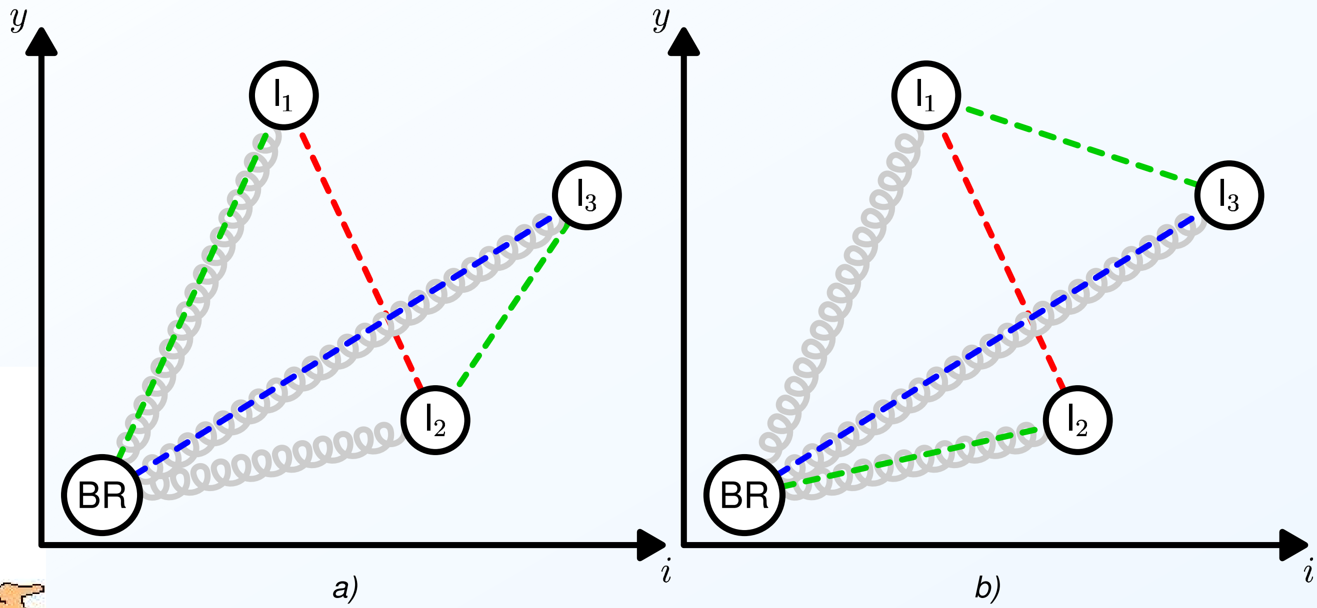


What is the colour flow?

What is the Colour Flow?

Possible ordering mechanisms:

- Always require physical colour flow (e.g. no singlet g).
- Simplest ordering is random, but gives *very* large multiplicity increase per interaction *and* large baryon number stopping.
- Tune A indicates that nature favours small increases in string length over large ones $\rightarrow$ try 'smarter' ways of connecting initial state colours.
  1. Random (but with suppression of remnant breakups)
  2. Ordering of connections by rapidity, Δy.
  3. Ordering by approximate string length, $\Delta\lambda$.

MODEL TESTS

Model Tests: FSR

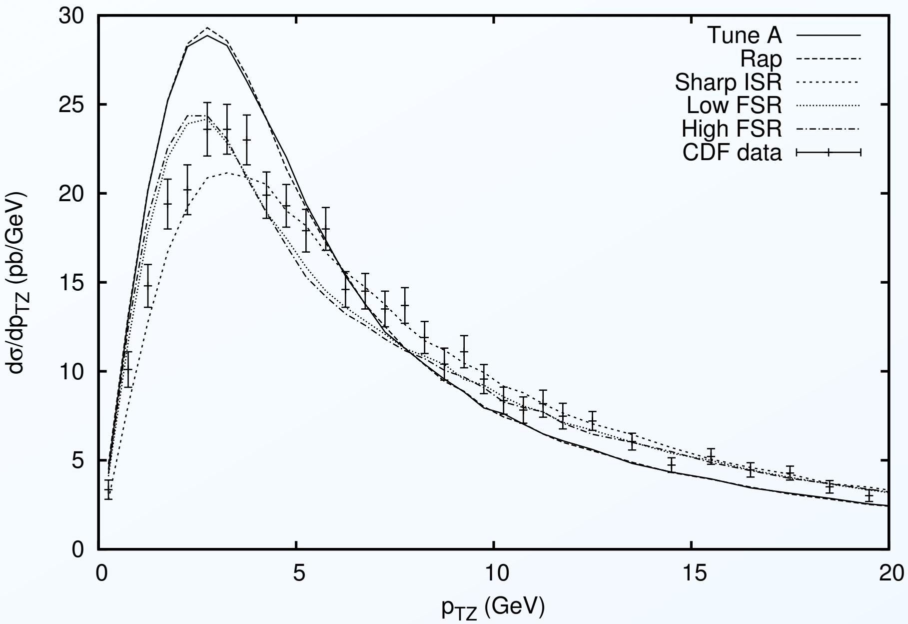
- FSR algorithm.
  - Tested on ALEPH data (G. Rudolph).

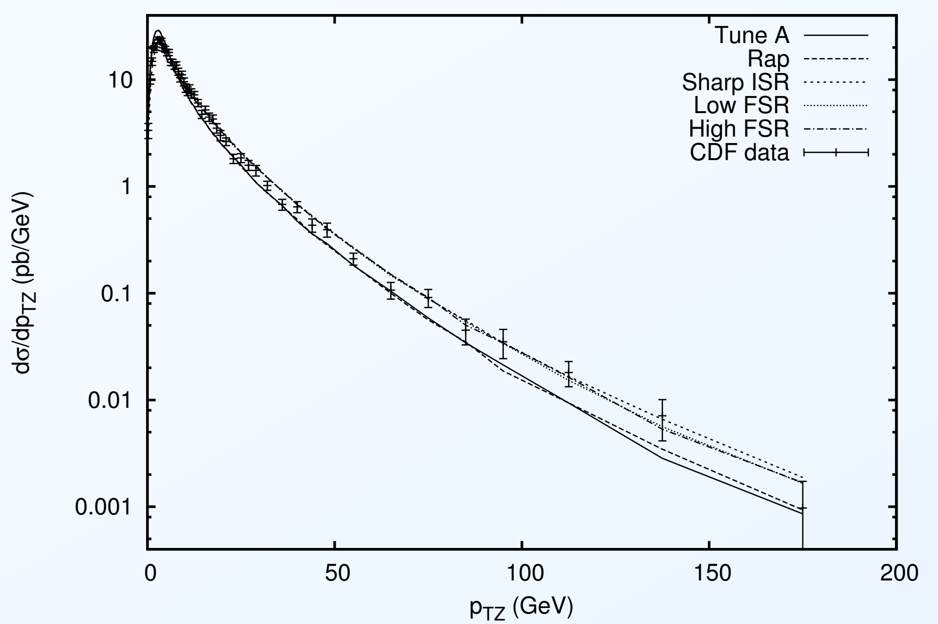
Distribution of		nb.of interv.	$\sum \chi^2$ of model PY6.3 $p_\perp$-ord.	PY6.1 mass-ord.
Sphericity		23	25	16
Aplanarity		16	23	168
$1-$Thrust		21	60	8
Thrust$_{\mathrm{minor}}$		18	26	139
jet res. y_3(D)		20	10	22
$x = 2p/E_{\mathrm{cm}}$		46	207	151
$p_{\perp\mathrm{in}}$		25	99	170
$p_{\perp\mathrm{out}} < 0.7$ GeV		7	29	24
$p_{\perp\mathrm{out}}$		(19)	(590)	(1560)
x(B)		19	20	68
sum	$N_{\mathrm{dof}} =$	190	497	765

  - (Also, generator is not perfect. Adding 1% to errors $\Rightarrow$ $\sum \chi^2 = 234$. i.e. generator is ‘correct’ to $\sim$1%)

Model Tests: ISR

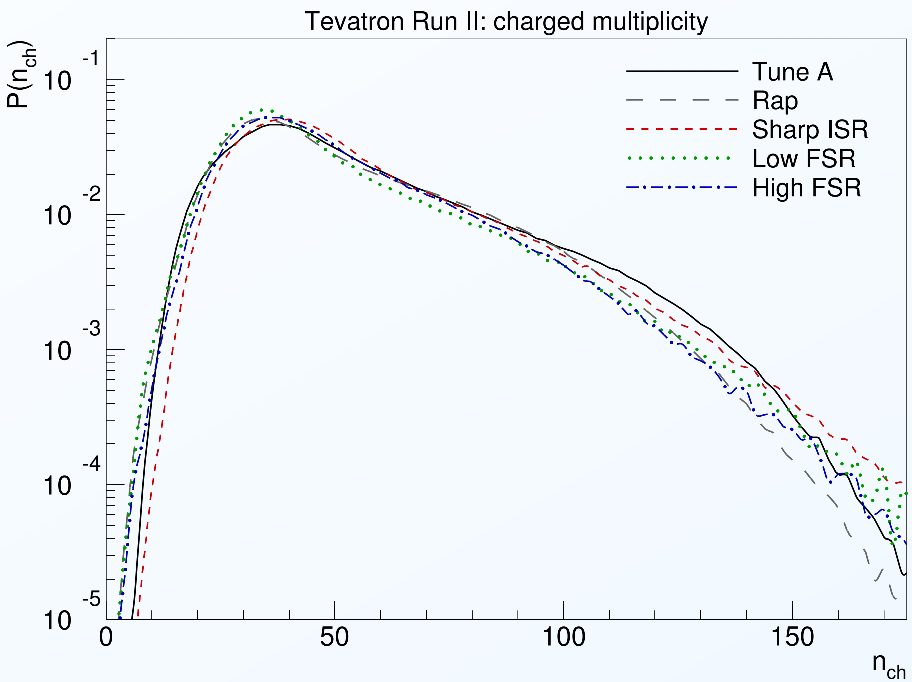
- ISR algorithm.
  - Less easy to test. We looked at $p_\perp$ of Z^0 at Tevatron.
  - Compared “Tune A” with an ‘intermediate scenario’ (“Rap”), and three rough tunes of the new framework.
  - Description is improved (but there is still a need for a large primordial $k_\perp$).

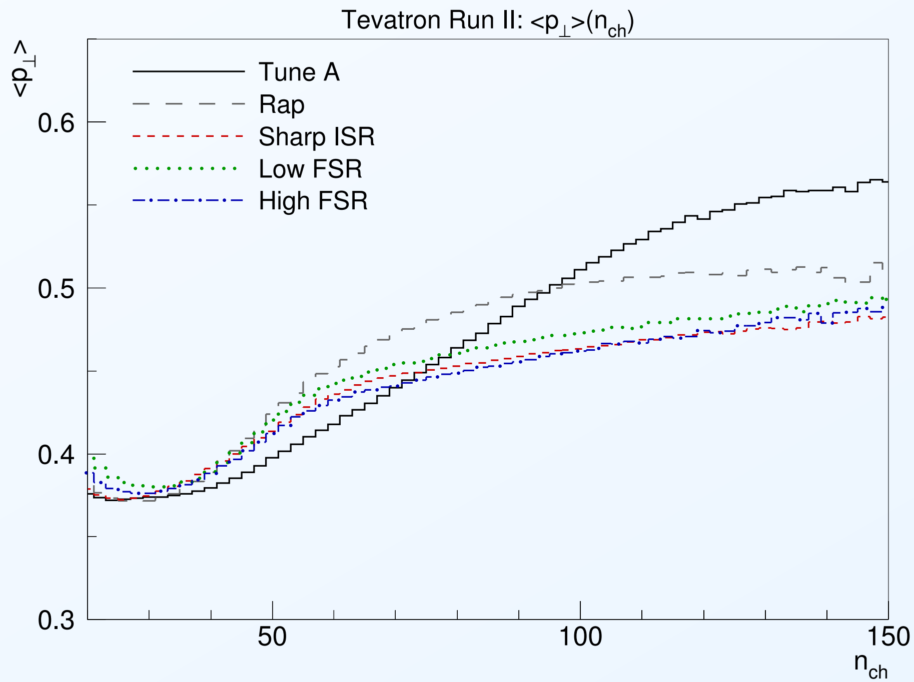




Model Tests

- Whole framework.
  - Produced a few rough tunes to 'Tune A' at the Tevatron, using charged multiplicity distribution and $\langle p_\perp \rangle(n_{\mathrm{ch}})$, the latter being highly sensitive to the colour correlations.
  - Similar overall results are achieved (not shown here), but $\langle p_\perp \rangle(n_{\mathrm{ch}})$ still difficult.
  - Anyway, these were only *rough* tunes...





The Next Step (ultra-brief summary)

- Tune A depends HEAVILY on high degree of colour correlation in the final state. So far impossible to reproduce with more 'physical' model (i.e. based on perturbation theory).
- Strangeness and baryon production anomalies at HERA $\rightarrow$ indications of similar phenomena?

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What will be done next is:

- Last 'desperate' attempt with P.T. at the MAX to get most highly correlated colour flow *without* reconnections. Continued failure would be interesting!
- $\rightarrow$ develop physical principles for collapse of colour wavefunction at hadronization and construct practical implementation. (Some ideas already.)

Outlook

- New complete framework for hadron collisions has been developed. Includes $p_\perp$–ordered *interleaved* parton showers and multiple interactions, correlated remnant parton distributions, impact parameter–dependence, extended (junction) string fragmentation model, etc.
- It's all in PYTHIA 6.315 (20 Oct 2004).
- Good overall performance, though still only primitive studies carried out, except for FSR.
- Colour correlations still a headache. Still unclear what role *intertwining* may play.
- Are jets universal or not?

Outlook

- New complete framework for hadron collisions has


Butch Cassidy and the Sundance Kid. Copyright: Twentieth Century Fox Films Inc.

- Are jets universal or not?
- But nobody said hadron collisions were easy...